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THEORETICAL AND EMPIRICAL STUDIES OF THE BASIC STRUCTURE OF TUR--ETC(U)  
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contour optimization. Separated Flows, Reattachment - Visual data on the structure of flow reattachment have been obtained; the data are clear and open the way to quantitative study. Good data on the backstep with variable angle opposite wall have been completed as part of a central predictive test case for the 1980-81 AFOSR-HTTM-Stanford Conference on Complex Turbulent Flows. Hydrodynamic Study on Concave Surface - Heat transfer on a concave surface is significantly higher than on a flat surface, other factors being equal. The present program is aimed at determining the mechanism responsible for this increase and means of predicting its occurrence. The approach is to construct a flow visualization and heat transfer experiment which at one time allows visualization of the flow structure and measurement of heat transfer rates. The studies are being conducted in a newly fabricated water test facility built expressly for this program. Heat Transfer Study on Concave Surface - Good progress has been made in design, fabrication, and validation of liquid crystal temperature sensing in water. This new technique should allow, for the first time, direct pictures of temperature distributions under turbulent boundary layers with and without streamwise vortical structures of a transient or steady form.

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(planar, conical, various annular types); they also cover compressible flows to  $M = 0.9$  and diffusers with unsteady free streams. The codes are not only very fast but give results in essential agreement with the entire range of known data for all but a few points involving special conditions as noted below. Moreover, when output is compared to the most accurate data, as for example that of R. L. Simpson and Co-workers or Ashjaee and Johnston, agreement is significantly better. Overall, we believe we are largely closing up practical computations of diffusers with straight centerlines. Strongly curving cases remain for future work. Some questions also remain regarding high turbulence core cases.

More specifically, the following developments have taken place during the past year. All work described is supervised by Professors Kline and Ferziger, the students who are responsible for the various components of the work are listed below.

a. A new entrainment correlation has been developed. The new correlation is as accurate as the old widely-used, Bradshaw correlation. However, it provides entrainment explicitly in terms of the shape factor for the boundary layer, and is therefore both easier to program and much faster in operation. Use of this new correlation sped up the diffuser program considerably and more importantly, it made feasible the unsteady boundary layer method and the inverse method of diffuser computation described below. (Students involved: A. Lyrio/J. Bardina)

b. A new skin friction correlation has been developed. This correlation is at least as accurate as the ones which were used previously; however, it is explicit and therefore easier to use. It also has the important advantage that it is applicable after separation. This correlation is now a standard component of our diffuser program. (A. Lyrio/J. Bardina)

c. The method developed for the computation of planar diffusers was extended to the annular and conical configuration. This involves the adaption of the boundary layer method to the axisymmetric case and the introduction of a one-dimensional axisymmetric core. The method developed is as accurate as the planar diffuser method. (Students involved: A. Lyrio/J. Bardina)

d. The boundary layer method has been extended to flows with unsteady inlet conditions. This has turned out to be surprisingly simple. We have found that the correlations used in the steady case can be employed. The method has been used to predict all known unsteady boundary layer data: predictions to data are again within the uncertainty bands. The only exception is some discrepancies in the one available data set that involves unsteady inlet conditions. These data are scant, further study is needed.

e. The unsteady method described in (d) above was used to construct a code for predicting the unsteady behavior of diffusers. In particular, we have been able to predict the data by Schachenmann and Rockwell and by Cousteix and Houdeville on diffusers with unsteady inlet conditions within the uncertainty of the data. These comprise all the known data sets. There are discrepancies at the exit plane in the data of Cousteix and Houdeville. It is not clear whether the difficulty lies in the experiment or the computation. (Student involved: A. Lyrio)

f. An analysis of the singularities in the equations describing turbulent boundary layers has been performed. It is well known that these equations become singular in the neighborhood of detachment. We analyzed the behavior of a number of possible boundary layer methods with prescribed pressure gradient and have shown that indeed any combination of equations become singular near incipient detachment (not full detachment) in a prescribed pressure computation. However, when a single boundary layer is allowed to interact appropriately with an internal core flow or an external potential flow, the singularity can be shifted in such a way that it no longer lies in the domain of computation. This analysis has played an important role in helping to develop the method of computing internal flows with the asymmetric boundary layers which is described in item "g" below. See also items (g) and (j) below. (Student involved: R. Childs)

g. A method of dealing with diffusers with asymmetric boundary layers has been developed. In the transitory and fully-developed stall regimes the stall is nearly all on one wall. The method of Bardina and Lyrio treats the diffuser as symmetric and includes a correction for the curvature near separation. The Bardina/Lyrio method could not treat asymmetric boundary layers because the equations became singular when two boundary layers were included. The difficulty has been corrected by interacting the separating boundary layer strongly with the core and treating the unseparated boundary layer as weakly interacting. This method has proved successful and is now being fully tested. This advance in the understanding of the singular behavior is an important step toward computation of detachment in strongly curving passages which is a future goal of the research.

h. An inverse or "stall margin" method of computing diffuser flows has been developed. In this method, the user specifies the distance of the boundary layer from detachment (in terms of shape factor) as a function of the downstream coordinate; the program then predicts the geometry of the diffuser. The method is based on the correlations used in the codes described in items (a) through (d). It has been tested against known diffusers with good success for both planar and conical geometrics. The method predicts that substantial improvements in diffuser design are possible for short diffusers with small inlet blockage and low inlet  $H = \delta^*/\theta$ . Smaller or negligible benefits are obtained in other cases. The results appear reasonable and we recommend that at least some of the proposed designs be tested. (Student involved: R. Strawn)

i. A method of computing compressible diffusers has been developed. This program will handle diffusers with inlet Mach numbers up to 0.9 and can be extended to handle all of the effects treated by the codes described above. (R. Childs). A sample of the results obtained in the diffuser computation effort are shown in the figures I-1 through I-5. Figure I-1 compares the prediction with the experimental data for a conical diffuser; the results are excellent. Figure I-2 compares the unsteady boundary layer prediction method with some recent data taken in our laboratory under another research program. The only discrepancies are near the wall and can be ascribed to the lack of a viscous sublayer model in our Velocity Correlation. Figure I-3 shows the maximum pressure recovery that can be obtained in a short diffuser; these results were predicted by the inverse method and are compared to the data of Reneau. The possibility of significant improvements is clear. Figure I-4 shows the results for a compressible diffuser. Figure I-5 shows the theory of

Bardina/Lyrio compared to the full range of the most accurate available data for planar diffusers with incompressible flow operating in transitory stall. No other theory is known. The agreement is remarkable not only for its overall accuracy but also because the operation of the physical limits on the entrainment equation shown as lettered points (B-C; X-Y; Z-W; F-G respectively) predict the flat spot seen in each case just after detachment and motion of the computation away from this limit condition correctly predicts the slow, roughly-linear pressure rise that is known from prior work under AFOSR sponsorship to be the characteristic "pressure signature" of transitory stall. The full implications in computation and in the physics of detachment are still under study in various ways.

j. Considerable further advance has been realized in our understanding of the processes of flow detachment and the correlation of it. The basic correlation was reported in the prior work year (1978-79). During the work year reported (1979-80) we have obtained further data using new instrument techniques developed in HTTM and have consolidated this understanding. We have come to realize that all earlier results both for detachment correlation and in regard to singular behavior of the computing equations have suffered from a basic confusion on a single point: the failure to distinguish incipient detachment from full detachment. This confusion in turn rests on the failure to understand the fundamental difference in the physics between a steady laminar detachment and a turbulent detachment on a faired surface. A steady laminar detachment is a location where the velocity gradient  $dU/dy$  is zero and hence the wall-shear is continuously zero. A turbulent detachment is a location where the wall-shear is only zero on the average, an average composed of significant transient values of shear both positive (downstream) and negative (upstream). The laminar, steady detachment occurs along a sharp line. The turbulent detachment is a region or zone that may be either short or long in the flow direction depending on the circumstances. These differences have important practical implications in the correlation of data, and hence in computation. Study of past visual data show that the visual methods all indicate incipient rather than full detachment. Similarly, a study of past correlations and criteria for detachment of the turbulent boundary layer show that the first occurrence of singular behavior is associated with incipient rather than full separation in marching schemes employing prescribed pressure. This result is general as can be seen from the fact that all 28 methods in the 1968 AFOSR-IFP-Stanford Conference on Computation of Turbulent Boundary Layers run into problems (and either fail or require ad-hoc fixes) well upstream from full detachment. Our singularity analysis, item (f) provides the reasons for these results in computation.

We have constructed an excellent correlation for incipient detachment of turbulent boundary layers. Thus we know when it is necessary to be careful concerning the possibility of singular behavior, and when to shift correlations from standard attached layer forms to detaching or detached forms. This information is well enough understood to be programmed. The same information is used as the basis for our "stall margin metric" and for specifying the shapes of optimum contoured wall diffusers with straight centerlines. The problem of optimum contouring has been attempted earlier by several other groups; however, we believe the boundary layer computation methods available to those groups were not of sufficient accuracy to settle the problem. We believe the methods reported above do have the requisite accuracy.



The successes in computation reported above all share a relatively high degree of physical input in the modeling and a relatively low degree of sophistication in the numerical codes (excepting the handling of singular behavior). It is thus the steady increase in understanding the underlying physics that has allowed us to create codes that are at once very fast and very accurate. A separate paper on this physics and its relation to correlations and implications for computations is nearly completed and will be presented to the AIAA meeting in Palo Alto, June 1981.

k. Flow over a backward step: The work order for this phase of work calls for construction of a new water channel, investigation of backward-facing step with variable step-side and opposite side wall angles, and study of the structure of the reattachment zones.

The basic flow channel is complete, and much of the effort during the 1979-80 work year has been occupied with installing and calibrating various instrument and visual techniques. The apparatus for visual studies are largely completed including a moving TV monitor system with very accurate means for measuring mean speeds. Various dye and hydrogen bubble techniques are in place and checked. A two-component, three-beam laser system has been purchased and has just arrived. Construction of a traverse platform and system calibration for the laser system remain for the coming year. The Thermal Tuft, an important instrument for measurements in zones of detachment and reattachment has been successfully adapted to water flows for the first time.

Using the thermal tuft, measurements have been made on reattachment length for varying angle of the opposite wall. These data provide a check on data from another laboratory for a central predictive case for the 1980-81 AFOSR-HTTM-Stanford Conference on Complex Turbulent Flows. (The check is excellent). Data for the variable stepside wall angle remain to be taken.

Dye slots installed near the reattachment line behind the back-step have provided excellent visualization of the flow structure. Although we have not yet had time to do quantitative recordation, it is clear that we have succeeded in illuminating the flow structure far more clearly than has been available in the past. We will move early in the 1980-81 year to record the central length and time scales of the three-dimensional transient structure observed at reattachment. Given this information we will be able to select a viewing frame that can be used to obtain clear simultaneous plan and side views to help further elucidate the structure and the flow dynamics.

As we expected the flow near the reattachment line is in some ways much like that at detachment. The flow consists of three dimensional elements that move upstream, then out from the wall, and then are again washed downstream. The size of the eddies is larger than in incipient detachment probably as the result of larger eddies in the oncoming free-shear layer. Given the variable speed TV monitor and the visual techniques now in place, we believe we will be able to clarify the relation between the coherent structures in the free-shear layer and the flow behavior at reattachment--a question that has been the subject of considerable recent controversy.

Annual Status Report, 3/1/81  
Contract AFOSR AF-F49620-79-C-0010

"Theoretical and Empirical Studies of the Basic Structure and  
Properties of Turbulent Shear Flows"

2. Work Area (cont'd)

Part II: The Heat Transfer and Fluid Dynamics of Concave Surface Curvature.

Principal Investigators: James P. Johnston and Robert J. Moffat

Preface

There is ample evidence that convective heat transfer on a curved surface is significantly different than on a flat surface: lower on a convex surface and higher on a concave surface. These effects are controlled by the fluid mechanic behavior and must be studied in that context. Curved surfaces exposed to high heat loads occur in many power systems of interest to the Air Force and are frequently the most vulnerable components of a system: e.g., nozzles in rockets and ramjets, minors in blast tubes, blades and vanes in gas turbines, and all curved internal flow passages. The fluid mechanic mechanisms by which heat-transfer augmentation occurs have been postulated, but as of the present time, there is no firm experimental evidence that these hypotheses are correct. Accurate prediction of heat transfer on the curved surfaces requires a proper understanding of the fluid mechanics involved. The discrepancy between curved- and flat-surface heat transfer may be as large as  $\pm 40\%$ , which is well beyond margin of safe design.

Introduction and Approach

Heat transfer on a concave surface is significantly higher than on a flat surface, other factors being equal. The present program is aimed at determining the mechanism responsible for this increase and means of predicting its occurrence. The approach is to construct a flow visualization and heat transfer experiment which allows simultaneous visualization of the flow structure and measurement of heat transfer rates. The studies are being conducted in a newly fabricated water test facility built expressly for this program.

It is currently believed that a basic flow instability leading to longitudinal roll-cells called Taylor-Gortler cells, is responsible for the increase of mean surface stress and heat flux. The flow structure is being made visible, and recorded, by photographic and television means. A synchronous stop-motion TV system has been purchased, which can be carried on a carriage at the mean fluid speed. This allows the evolution of the boundary layer structure to be studied in detail, using a frame of reference moving with the mean fluid speed. The heat transfer will be made visible and quantitatively evaluated by a new liquid-crystal technique developed at Stanford. Recent work has shown that an electrically heated liquid crystal film can be used to make visible a line along which the heat transfer coefficient,  $h$ , is constant. This technique had previously been developed and demonstrated in air and has now been adapted to water studies for the current program.

### 3. Status of Research Effort (cont'd Part II-A)

This research program has been under way for about two years. The first year's work entailed the design and construction of the large-scale water-flow apparatus described in the proposal (MET 37-38) and the development of the liquid-crystal heat transfer technique. During the past year the curved apparatus was brought up to full operational status, and preliminary experiments using dye flow visualization have been conducted. In addition, the liquid-crystal technique has been perfected, and the special curved wall for the heat transfer experiment has been built.

A highlight of the curved wall channel-design process was the use of numerical computation of the potential flow and the turbulent boundary layers on the channel walls, so that the streamwise pressure gradients on the concave test wall (90° turn at a radius of 136 cm) and on the flat walls upstream and downstream (recovery region) would be negligible. We used the method of potential flow analysis developed previously, under AFOSR sponsorship, by Kline, Woolley, White, Ferziger and Bardina.

A probe-traversing mechanism using stepping motors for actuation with remote digital control was built and installed. This device, when mounted on the self-propelled carriage which runs on the rails over the channel walls, permits three-axis probe location: x-axis or streamwise motion, y-axis motion to the wall and perpendicular to the streamwise direction.

Hot-film anemometers were tested in the flow for use in measurement of the streamwise component of mean velocity,  $U$ . The air content of the water was lowered to the extent needed for hot-films to operate with some changes in system's design to reduce aeration by bubble entrainment at the channel outlet, and by completion of the system's de-aeration equipment.

The clear plexiglas curved channel walls have been installed and experiments commenced. Spanwise dye slots are located in the test wall at the mid-span region, far enough away from the free surface (top) and the channel bottom to avoid the effects of cross-flows generated in the curved region near top and bottom surfaces. The region of nominal two-dimensionality appears to be larger than the  $z = 30.5$  cm span length of the dye slots. Cameras were situated approximately as shown by the four viewing "eyes" in Fig. II-1. Television, motion picture, and still cameras were used to visualize the flow in the  $x$ - $z$  plane. The flow was marked by the red and blue neutrally buoyant dyes from pairs of dye slots at the various viewing locations. A short motion picture film of these early data was prepared and presented at the November 23-25, 1980, meeting of the Division of Fluid Dynamics of the American Physical Society.

Some representative still pictures of the results are shown in Figs. II-2 and II-3. In views a, b, and c, the speed of the water at the edge of the boundary layer was  $U = 15.2$  cm/s. The thickness of the turbulent boundary layer at the downstream end of the upstream flat wall (view a) was estimated to be 7 cm. Measurement of the layer is now under way using a hot-film anemometer.

View a shows the wall-layer streaks characteristic of a turbulent boundary layer. The bursting of the streaks is easily seen in the movie.

View b was taken about 120 cm (17 boundary layer thicknesses) downstream of view a, in the curved wall region. The wall-layer streaks are still present, but we also see new, larger-scale gatherings of the red and blue dye near the wall. These and other visual observations show that the dye gathers along the wall in plumes, spaced roughly 10 cm apart in the spanwise direction. Flow is strongly away from the wall inside these plumes as noted by the fact that the blue dye rides over the red dye, which was injected downstream of the blue. Motion pictures show that the large-scale plumes are not static but appear to form and wash away on a long and erratic time scale. The spanwise locations and the widths between the plumes also change with time.

View c was shot downstream of the curved surface on the flat recovery wall. Here we still see evidence of the existence of the large-scale plumes which have been convected out of the curved region. The typical smaller scale wall-layer streaks are also in evidence, but the movies show less vigorous turbulent bursting than is seen on the flat wall upstream of the concave curved wall.

View d was shot with a lower water velocity, so that the boundary layer ahead of the curved wall would be laminar. Note the absence of wall-layer streaks on the left-hand side of the picture (the flat, upstream region). In the curved region, we see large-scale plumes clearly. At the right-hand side of the view, the upwelling, low-momentum, wall-layer fluid appears to trigger shear-layer instabilities, very similar to those seen in the flow of laminar, buoyant plumes and wakes.\*

The detailed interpretation of these results is yet to be undertaken. However, the existence of the large-scale, "buoyant" plumes of low-momentum wall-layer fluid in both turbulent and laminar boundary layers is clear evidence of the instability phenomenon discussed in the proposal for this work.

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\* /See the film "Eddies in Captivity," by A. E. Perry, University of Melbourne, Melbourne, Australia.

### 3. Status of Research (cont'd, Part II-B)

#### Heat Transfer for Turbulent Boundary Layer on a Wall with Strong Concave Curvature.

Although no studies have as yet been made in the concave region, a great deal of progress was made during the past year. As was mentioned earlier, the first year's effort was largely devoted to bringing the main tunnel on line. When the tunnel status reached an acceptable level, the heat transfer effort was turned to validating the liquid crystal technique for quantitative work in water. Four principal tasks were accomplished: (1) proof of uniformity of the liquid crystal temperature indicator, (2) proof of uniformity of the heat release from the vapor deposited gold, (3) analysis of the response of the system to fluctuating heat transfer, and (4) packaging for water-tightness and electrical integrity.

A water-bath, controlled to within 0.01C was used to test samples of the liquid crystal material at different temperature levels, and the material shown to be uniform, as received, from batch to batch and sample to sample. The trigger temperature and the ambiguity band were determined for the type of paint used. Long term stability tests were started, to determine the effect of water immersion on the characteristics of the liquid crystal material.

A technique was developed for measuring the total heat release per unit area of the gold film material. The technique finally adopted pinches the sheet between two thin-film heat flux gages connected in series addition. The total signal represents the total heat release, since the gages are linear. Mapping of several samples has shown that the heat release is uniform within  $\pm 10\%$  of the mean value on any one sheet. Figure II-4 shows a typical map of the distribution of heat release on a sample. This is the principal component of uncertainty in the application of the method, and could be taken out only with great difficulty. In cases where 10% is not sufficient accuracy, one approach would be to repeat the same measurements using several samples and average their results. If the samples were independent, the average should be better than  $\pm 10\%$ .

The dynamic response of the sensor system is of great importance to the success of the present program. The concave wall is expected to introduce two effects, both of which may affect the surface heat transfer: (1) the turbulence within the boundary layer will be augmented, by the same mechanism responsible for its suppression in the convex case, and (2) there may develop longitudinal vortices of the Taylor-Goertler type. One objective of the present program is to determine whether or not both mechanisms are important in setting the heat transfer level. If the vortices were present, and remained fixed in location on the surface, then their effect could certainly be seen by a sensor system of the liquid crystal type, even if it had only "steady-state" performance capability. If, on the other hand, the vortices were present, and did affect the heat transfer, but meandered across the surface at some frequency, then the liquid crystal system would have to be designed to have sufficient frequency response to respond to the passage of a moving vortex across the surface. No simple way was known to test for the effect of a varying surface heat transfer coefficient, directly. However, it is quite simple to vary the heat release within the gold film: one need only vary the power provided. A test fixture was built for this purpose, allowing

the frequency and amplitude of the fluctuation to be selected, over a broad range. An analysis was made of the temperature-time response of the liquid crystal film under conditions of varying heat release with a steady heat transfer coefficient, and also for the case of steady heat release with a varying heat transfer coefficient. It was shown by the analysis that the temperature-time response was very nearly the same. This provided the necessary "calibration" so that tests at varying heat release could be used to simulate the effects of varying heat transfer coefficient. The results of the two analyses are shown in Figure II-5 and Figure II-6, respectively. Figure II-6 shows that varying the heat release rate at 1.5 Hz should cause the mean color line to fluctuate visibly. This same degree of visibility would be achieved, with constant heat flux and varying heat transfer coefficient, at a frequency of 1.0 Hz. Tests were conducted in the water tunnel, applying a sinusoidally varying heat flux to the film at various frequencies. At 3.2 Hz the color fluctuation was clearly visible.

The dynamic response of the film sensor has been shown to be good enough to reveal the presence of fluctuations in the heat transfer coefficient, if they exist, provided that their amplitude is at least  $\pm 10\%$  and their frequency not higher than 3.0 Hz. The film sensor will not provide quantitative data concerning the magnitude during the transients, but will signal that transients are present, and more than 10%.

Several different electrode systems, lead wire attachments, and packaging techniques were investigated, aimed at producing water-tight units which would be electrically safe, and of reasonable cost for production. The final design uses a Plexiglas frame, with the liquid crystal sheet cemented to the front face, with a Plexiglas back cover through which the electrodes pass. The unit is assembled, taped around the edges with thin Mylar tape, and then epoxy encapsulated. This design has been finalized, and released for production.

Considerable effort has gone into selecting the best light source, lighting angle, viewing angle, and type of filter to be used on the camera and on the T. V. recorder. Surface markers have been selected and applied, to provide a reference grid: problems of halation of the image on the high contrast vidicon tube were solved by using colored, as opposed to white markers. Black and white, the color photographic techniques have been finalized, as have the video techniques.

Calibration tests have been conducted in pure free-convection, with excellent agreement between the measured values and those reported in the literature.

Calibration tests in forced convection are now under way. It is planned to run both a flat plate test, and a Falkner-Skan wedge flow of 6 degrees angle. These should provide the final proofs needed.

Figure II-7 shows a demonstration of the method, applied in the Stanford water tunnel. A vertical flat plate, one of the standard packages, was installed with a short cylinder held in contact with it, perpendicular to the plate surface. The water flow is from left to right in the picture. The isochrome marks the locations where the heat transfer coefficient is 400 watts/m<sup>2</sup>. Fluctuations were clearly visible in the wake, far downstream, but none were present near the cylinder.

Once the forced convection calibrations are finished, the technique is deemed ready for application.

The heat transfer test wall has been designed and built, incorporating pockets for 14 of the fim sensor packages. The 14 units will provide three upstream of the curve, seven in the curve, and four in the recovery region. As soon as 14 packages are finished, the wall will be assembled ready for installation into the tunnel.

A power control console, the power supply for the unit has been designed, and fabrication is about 70% complete. The console allows individual control of the power to each of the 14 panels in the heat transfer research test wall. By this means it is possible to set up an isothermal test wall, or to investigate the effects of steps in wall temperature in preparation for generalizing the study.

#### 4. Publications

##### A. 1979-80 Period

1. "The Structure of Turbulent Boundary Layers," Citation Classic, Current Content, 32, 6 August 1979. S. J. Kline, W. C. Reynolds, F.A. Schraub, and P. W. Runstadler (this reports the history of a now classic paper done under prior AFOSR support; it amounts to an award).
2. "Investigation of a Reattaching Turbulent Shear Layer: Flow over a Backward Facing Step," by J. Kim, S. J. Kline, and J. P. Johnston. ASME Symposium, Dec. 1979, "Flow in Primary Rotating Passages in Turbomachines." (Also under review by J. Fluids Engrg.)
- 3/ "A Procedure for Computation of Fully Stalled Flows in Two-Dimensional Passages," Proc. ASCE-IAHR/AIHR-ASME Joint Symp. on Design & Operation of Turbomachinery, Vol. I, June 12-14, 1978; also in TASME J. Fluids Engrg. 100, 4 December 1978, by R. L. Woolley, S. J. Kline.
4. "The Computation of Optimum Pressure Recovery in Two-Dimensional Diffusers," J. Fluids Engrg. 100, 4 December 1978, pp. 419-426, by S. Ghose, S. J. Kline.
5. "The Role of Visualization in Study of the Structure of the Turbulent Boundary Layer," invited keynote address in Proc. of AFOSR -Leigh Conference on Structure of Turbulent Boundary Layers, Lehigh University, held May 1978, by S. J. Kline.

##### B. Completed during 1979-80

1. "A Prediction Method for Planar Diffuser Flows" by J. Bardina, A. Lyrio, S. J. Kline, J. H. Ferziger, and J. P. Johnston; to be published in Journal of Fluids Engrg, Trans. ASME.
2. "Measurement, Correlation and Computation of Dettachment and Reattachment of Turbulent Boundary Layers on Faired Surfaces", S. J. Kline, J. G. Bardina, A. Strawn. (Accepted for AIAA meeting Palo Alto, CA, June 1981).
3. "Summary of AFOSR/MSU Research Specialists Workshop on Coherent Structures in Turbulent Boundary Layers: July 30-August 1, 1979", S. J. Kline and R. E. Falco. (Report CSL-80-1; issued by Michigan State University Draws extensively on AFOSR sponsored work at Stanford).
4. "The Effects of Concave Curvature on Turbulent Boundary Layers", A. H. Jeans and J. P. Johnston at Amer. Physical Society, Div. of Fluid Dynamics, November 23-26, 1980.



C. In Process

Three major reports on Diffuser Computations are in process and due for completion in 1981. Subjects (not exact titles) are as follows:

1. "Computation of Planar and Annular Diffusers. (Will include:(a) improved correlations for detachment and for skin friction; (b) review of annular diffuser literature with improved correlations for optimum designs; (c) extensions of the Sovran-Klomp correlation for optimum diffuser performance as a function of inlet blockage). By J. Bardina, S. J. Kline, J. H. Ferziger.
2. "Computation of Conical Diffusers and Diffusers with Unsteady Free-Stream Flows". (Includes improved entrainment correlation and limit bounds for effective computation of cases with large stall present). By A. Lyrio, J. H. Ferziger, S. J. Kline.
3. "Computation of Diffusers with Compressible Flow to  $M \approx 0.9$ . By R. Childs, J. H. Ferziger, S. J. Kline.

5. Professional Personnel Associated with the Project

Faculty: Prof. S. J. Kline, J. H. Ferziger,  
Prof. J. P. Johnston, Prof. R. J. Moffat  
Dept. Mech. Engrg.

Visitors: Prof. E. Yamazato, Univ. of the Ryukus,  
(work on diffuser experiment and computation)  
Prof. S. Honami, Tech. Univ. of Tokyo,  
(work on curved surface boundary layers)  
Prof. N. Kasagi, Univ. of Tokyo  
(A developer of liquid crystal techniques)  
Prof. H. Nagib, Ill. Inst. Tech.  
(work on visualization, computer use)

Research Assistants: (All PhD Candidates)  
J. G. Bardina, A. Lyrio, R. Childs, R. Strawn  
(work on diffuser computations)  
S. Pronchick  
(work on reattachment, back-step)  
A. Jeans  
(Hydrodynamics of Concave wall)  
J. Simonich  
(Heat transfer of concave wall)

On closely related projects and contributors to ongoing research seminar:

Prof. J. K. Eaton  
(work on instruments; developer of thermal tuft and wall-shear probes; work on reattachment zone in air-compliments water study)

Research Assistants:

- A. Ashjaee (Transitory stall data)
- A. Cutler (Asymmetric diffuser flows)
- R. Westphall (Wall-shear probes of new types; backstep flows with variable angle)

6. Interactions (Coupling Activities)

The results of the diffuser computations, inverse design procedures, stall margin concepts, and progress of techniques in wall curvature and instrument development were all presented at the Thermosciences Affiliates Meeting. This group comprises 21 leading industrial corporations that contribute to and follow the work. Workers from Boeing, NASA Ames Lab, AiResearch, General Electric, General Motors, United Technologies are included.

Professor Kline gave talks on the diffuser work and wall curvature work to a meeting of engineers from Brown Boveri and Sulzer Corporation in Zurich and to Chemical Systems Division of United Technologies. Professor Kline also contributed to the AGARD meeting on viscid-inviscid interactions in Colorado Springs.

Professor Johnston visited with and consulted for AiResearch on problems of diffusers and turbomachinery.

Professor Ferziger has been invited to give lectures on numerical methods at the von Karman Institute in Brussels.

Professor Moffat has created important advances in uncertainty analysis and discussed these with leading workers nationally, including DOD experts on testing and reliability.

7. New Discoveries, Inventions, Patents Applications

No new patents were filed during 1979-80.

Applications of the improved correlations for friction and detachment are very numerous. Included are calculations for wing flows, inlets, turbomachinery. Improved sensors for stall inception and for measurements in regions of detachment and reattachment have begun to be applied not only in this project but also in several other projects in HTTM and in at least one research at NASA Ames. With publication in 1980, we expect more rapid diffusion of applications in coming years since no other available instruments fill the same measurement niche.

8. Other Information

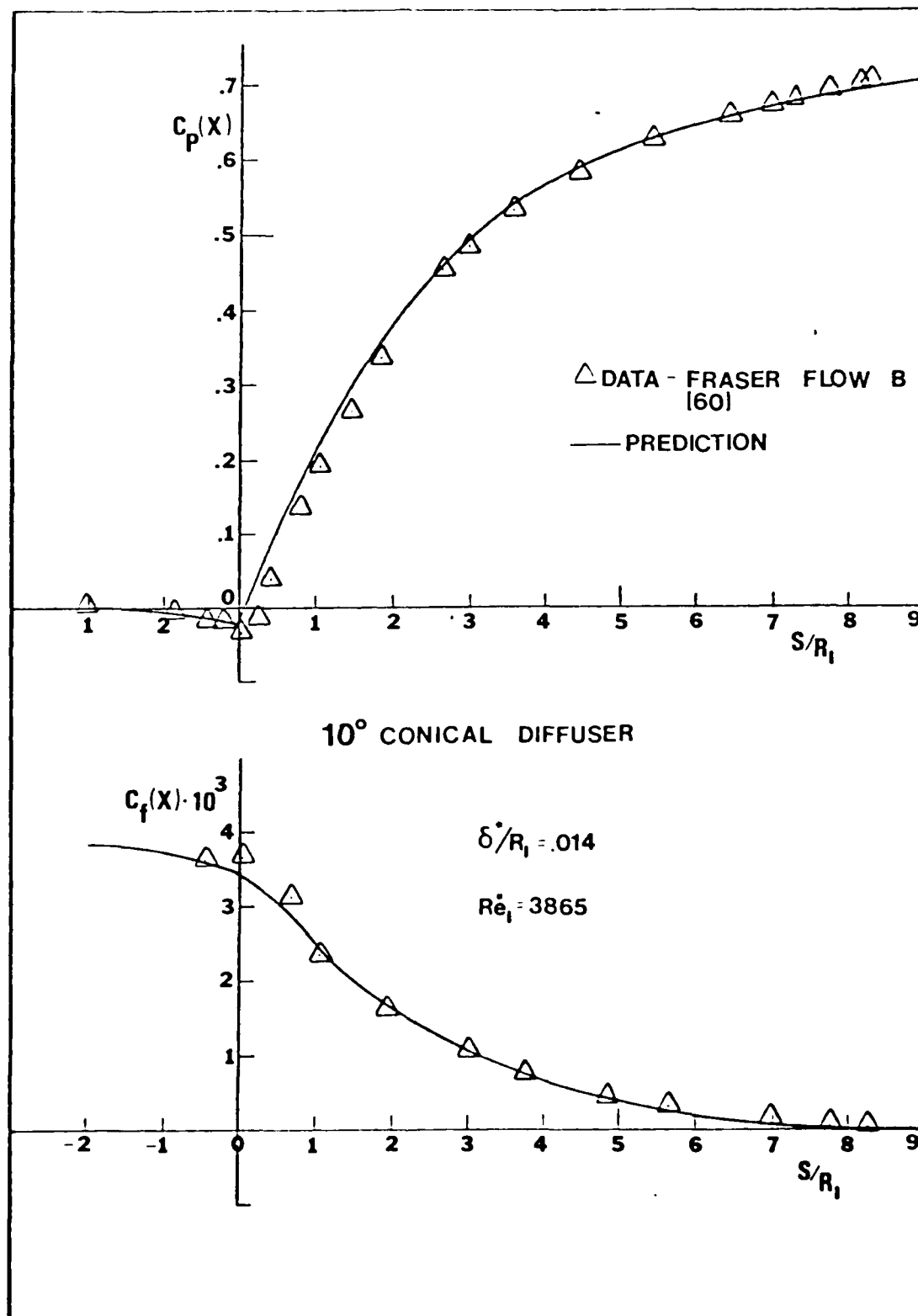
The very rapid progress in diffuser computation, optimization, stall margin calculations, and on the physical understanding of flow detachment during 1979-80 are a culmination of accumulating pieces of new knowledge and techniques going back to the early 1970's. They combine not only wholly new knowledge and methods, but also a number of minor improvements and fine-tunings that collectively have important impact on the speed and

accuracy of computation and allow movement forward into more complex situations as for example unsteady free stream flows with turbulent boundary layers in passages. This accumulation of bits of needful knowledge ultimately giving rise to rapid progress is an important factor underlying the importance of continued, long-range efforts by coordinated groups as opposed to one-shot research projects. It is certainly true in the work reported in Part I above that no one or even a few bits of this knowledge are sufficient for the gains achieved; it is rather the synthesis of the whole that was required.

As noted in Part I, item 3 on Progress above, we have largely closed up computation methods for diffusers with straight centerlines for many purposes. We still need to produce a fully commented set of programs that can be more widely disseminated to industry on a single tape. This is however not a large task. We intend accordingly to move forward in the 1980-81 year to the problem of computation of diffusing passages with strong wall curvature. It is noteworthy that the combination of such passage computation with the transient methods already achieved would move computing ability very close to practical computations for the real flows turbomachinery passages.

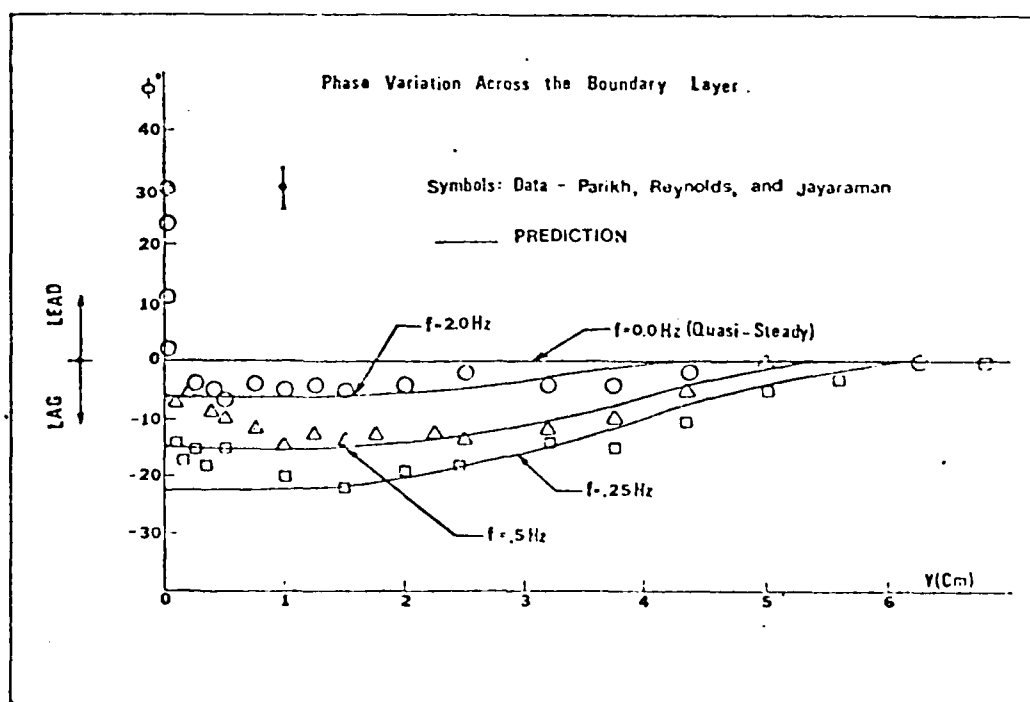
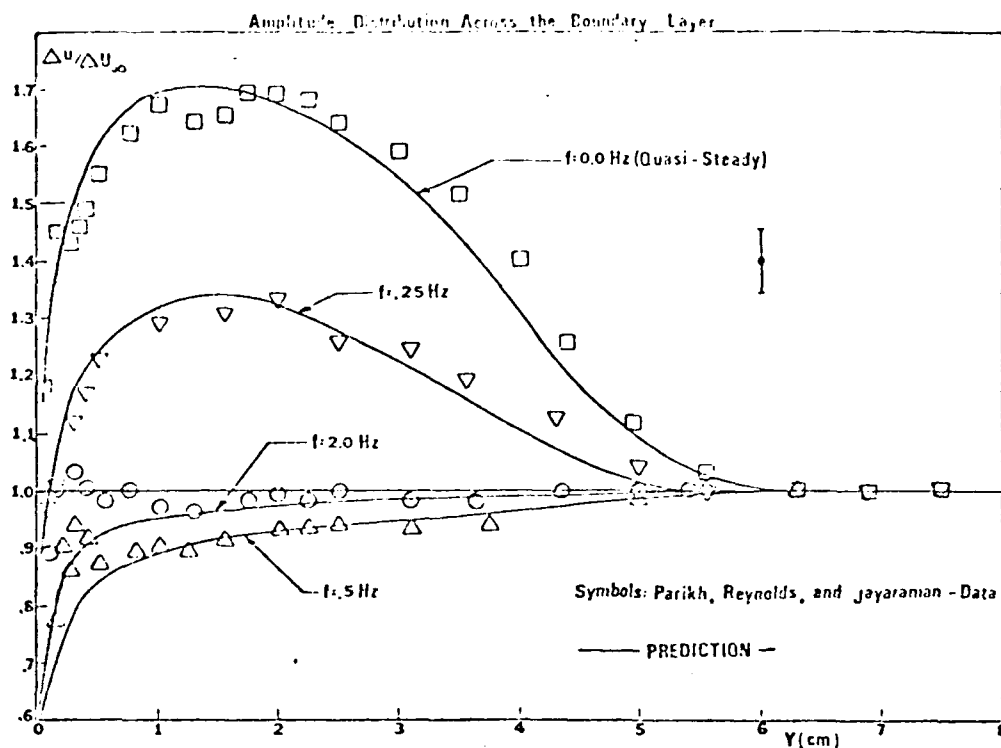
It is also noteworthy that a group of Research Assistants together with Professor J. H. Ferziger are applying the fast, accurate passage computation methods of Part I above to flows for the 1981 meeting on Computation of Complex Turbulent Flows. The group expects to produce computations for approximately half of the incompressible trial cases for the conference.

FIGURE I-1



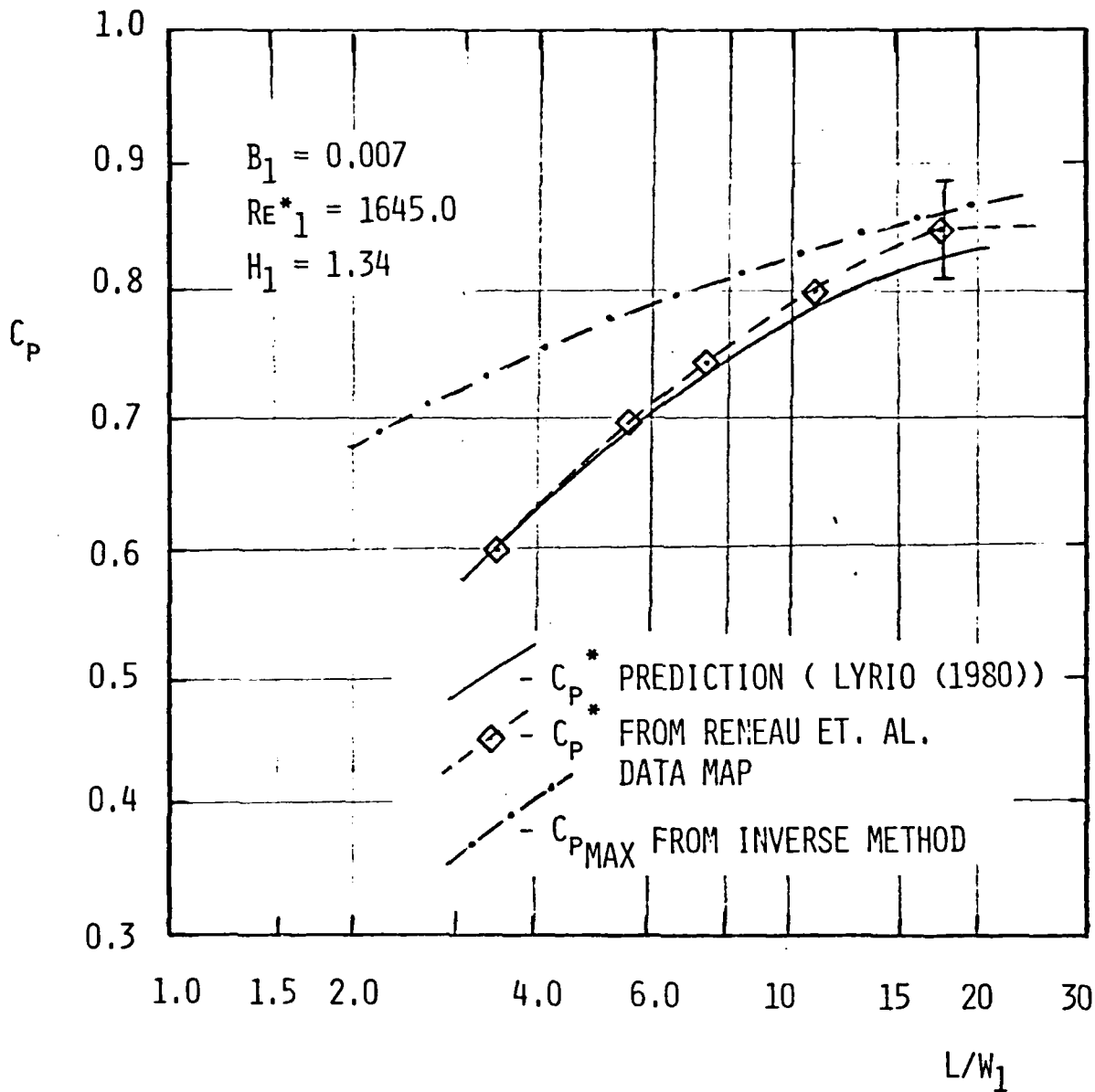
RESULTS OF CONICAL DIFFUSER PROGRAM OWING TO A. LYRIO FOR FRASER B FLOW. (NOTE THIS FLOW WAS NOT PREDICTED WELL BY ANY METHOD IN THE 1968 AFOSK-IFP STANFORD CONFERENCE)

FIGURE 1-2



COMPARISON OF THEORY OF A. LYRIO WITH RECENT UNPUBLISHED DATA OF PARIKH, REYNOLDS AND JAYARAMAN (STANFORD) UNSTEADY TURBULENT BOUNDARY LAYER

FIGURE I-3



COMPARISON OF  $C_p^*$  FROM RENEAU DATA MAP  
TO  $C_{pMAX}$  FROM INVERSE METHOD

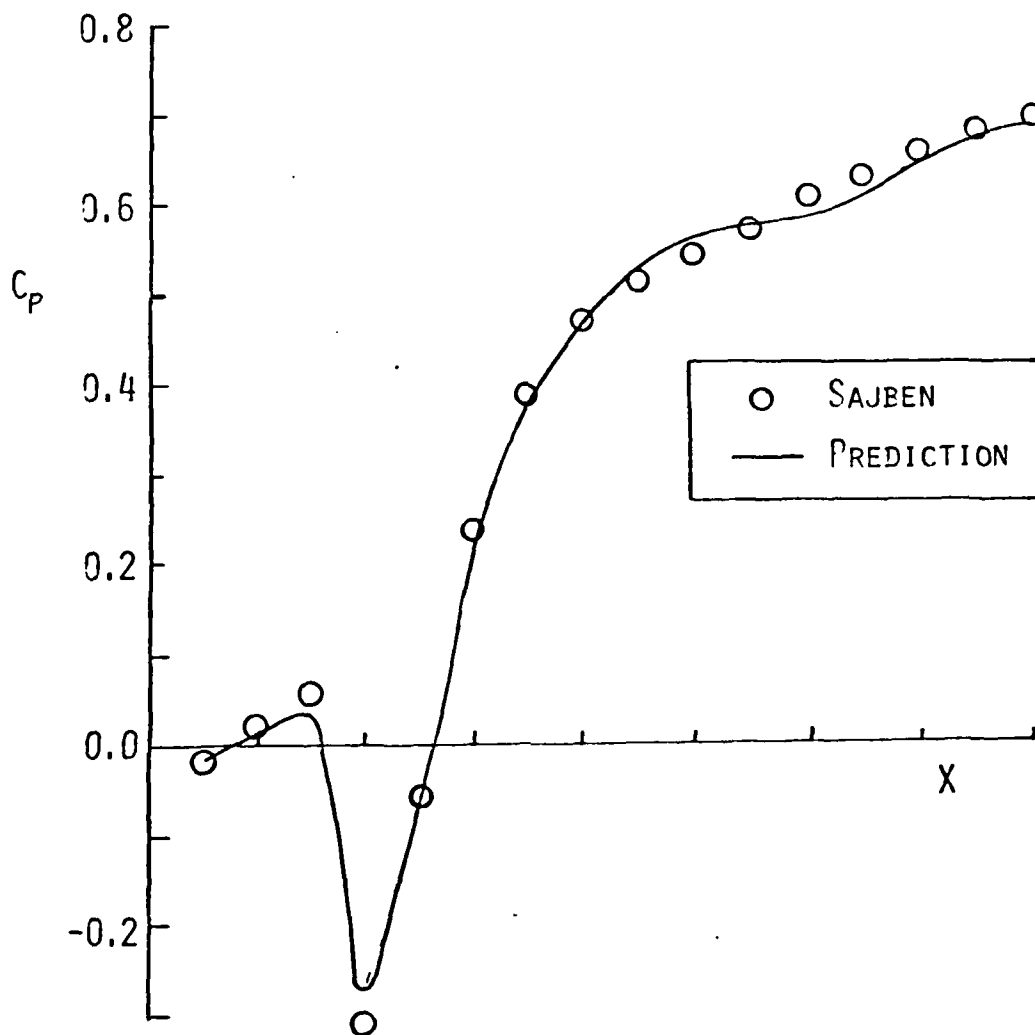
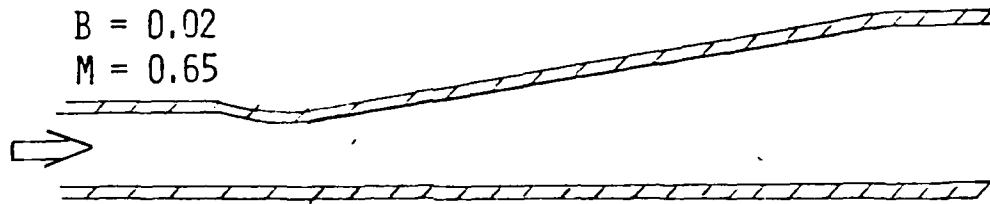
EFFECT OF OPTIMIZING WALL COUNTOUR FOR LOW  $B_1$  AND  $H_1$

FIGURE I-4

COMPRESSIBLE DIFFUSER

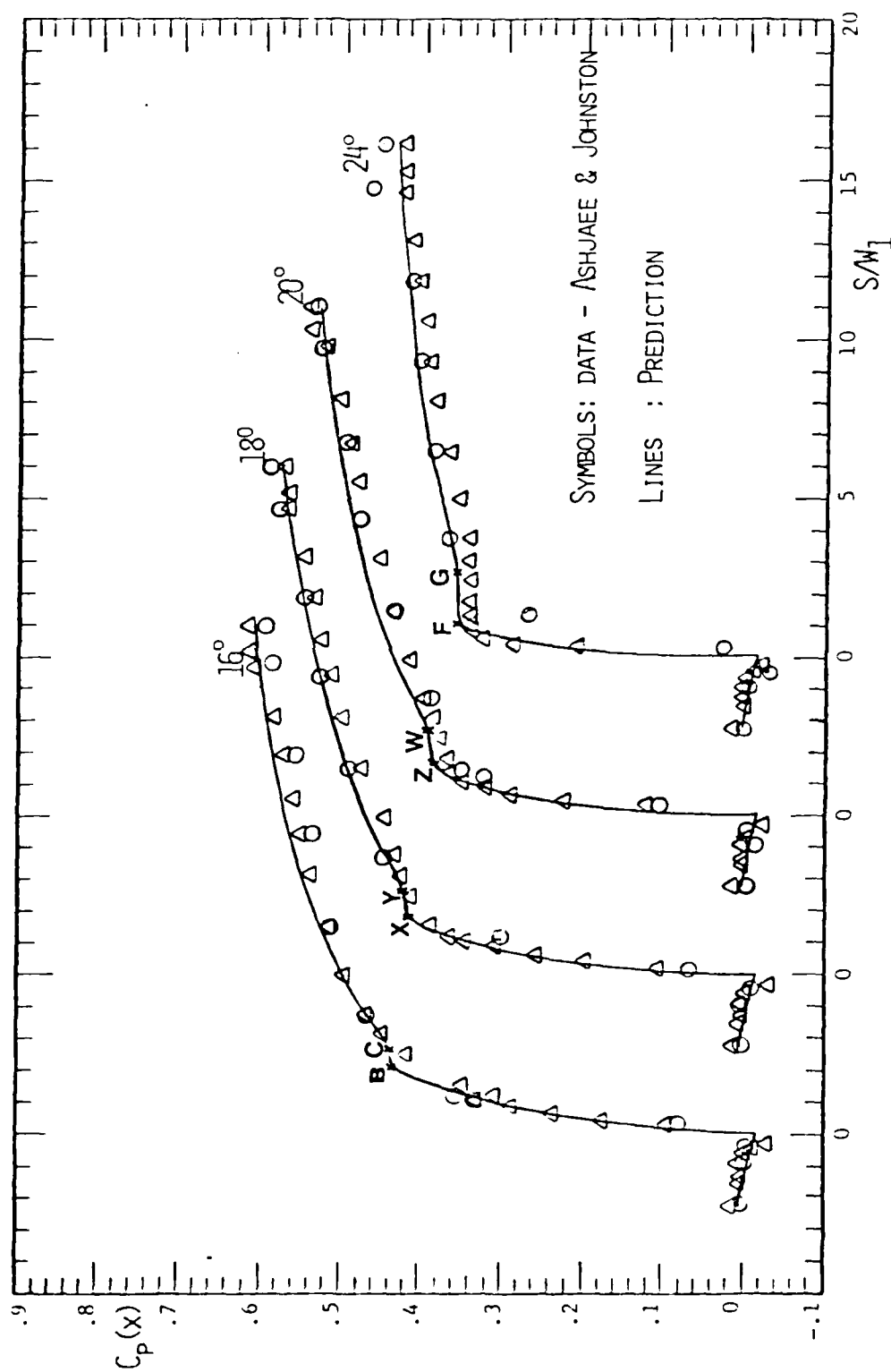
$$B = 0.02$$

$$M = 0.65$$



COMPARISON OF THEORY OF R. CHILDS WITH DATA OF SAJBEN  
(MCDONNELL DOUGLAS) FOR SUBSONIC COMPRESSIBLE DIFFUSER

FIGURE I-5



THEORY OF BARDINA/LYRIO COMPARED TO DATA FOR FULL RANGE OF TRANSITORY STALL IN PLANAR OR DIFFUSERS. LETTERED POINTS ON EACH CURVE INDICATE START AND STOP OF LIMIT BOUNDS FOR ENTRAINMENT EQUATION



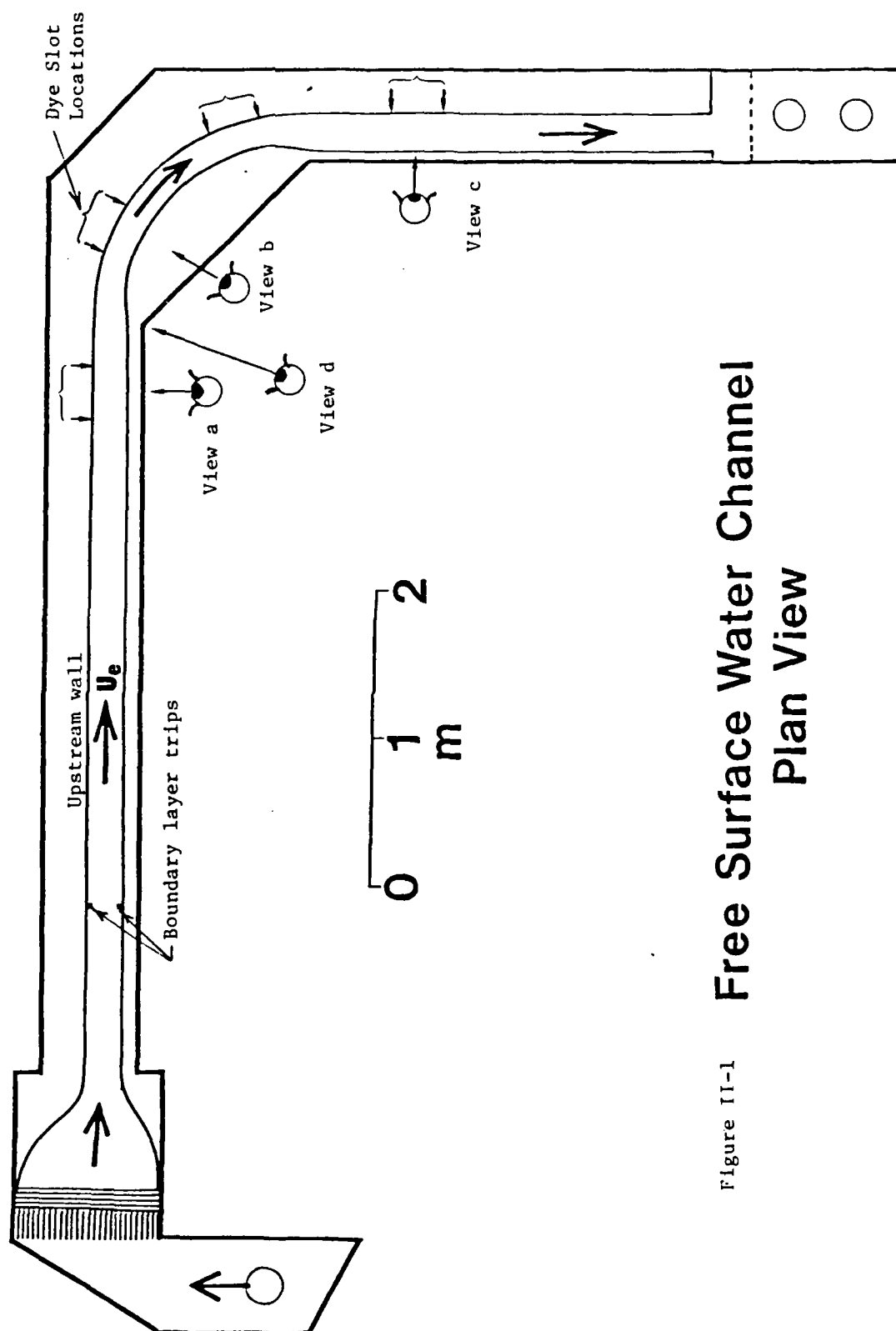
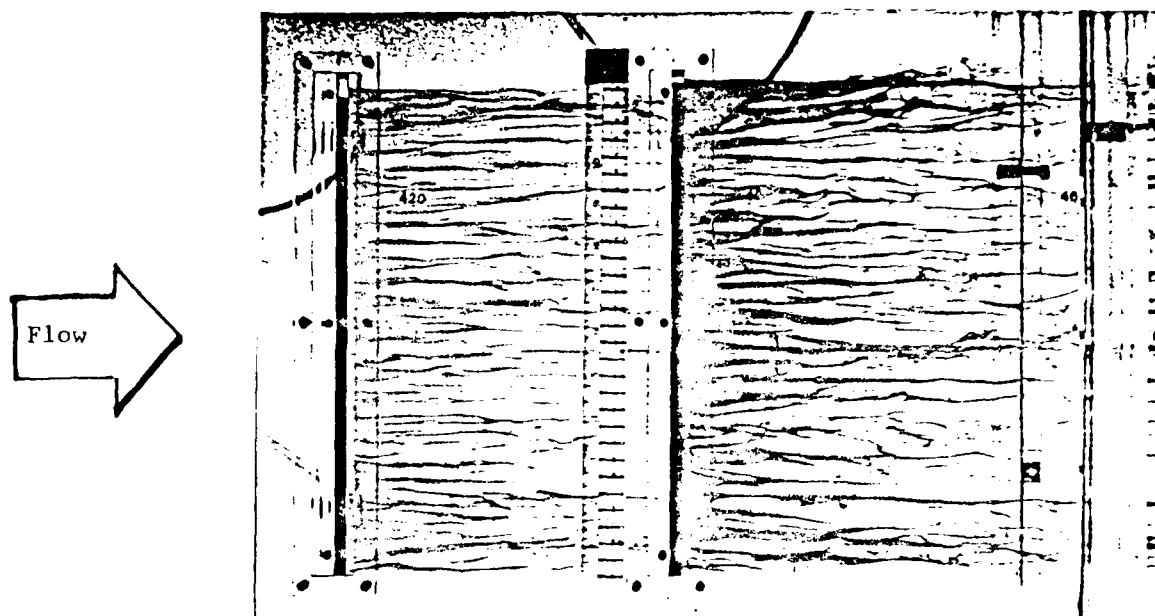
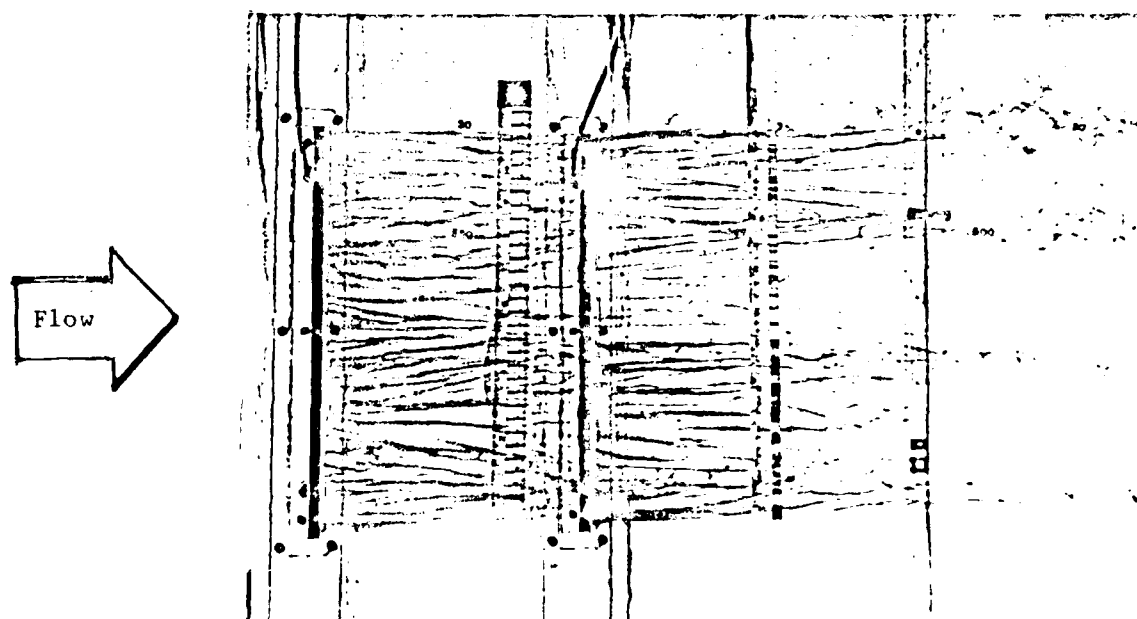


Figure II-1 Free Surface Water Channel  
Plan View

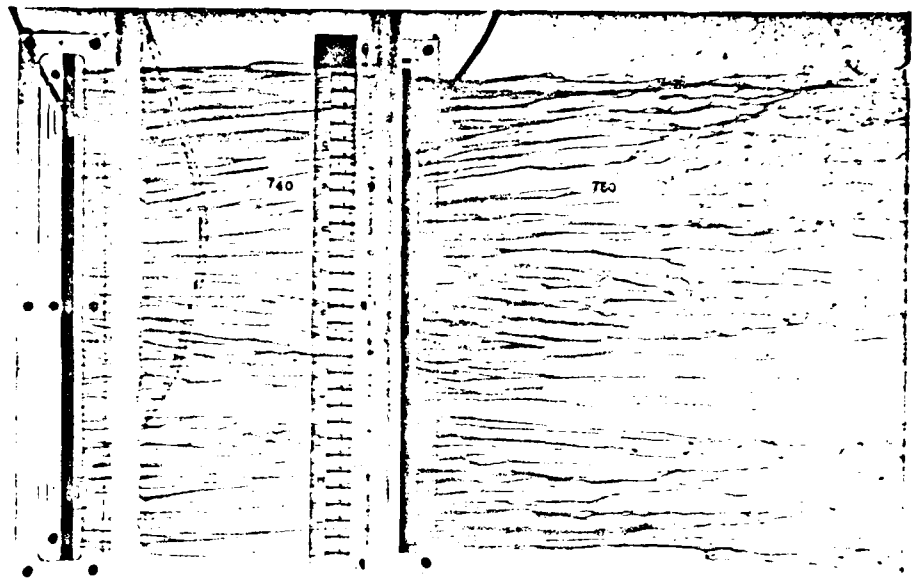
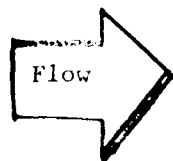


View a Flat wall just ahead of curved region from  
 $x = 415 \text{ cm. to } 460 \text{ cm.}$   $U_e = 15.2 \text{ cm/s}$

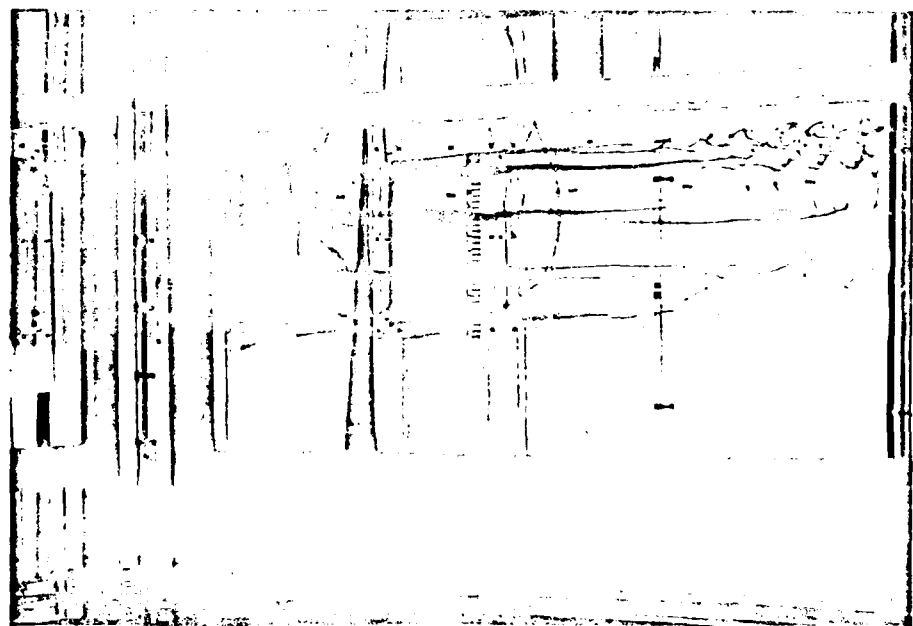
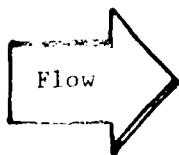


View b Curved wall, over an arc  $25^\circ$  to  $50^\circ$ ,  $U_e = 15.2 \text{ cm/s}$

Figure II-2 Dye injected into wall layers through two spanwise slots  
 30.5 cm. long and 20.3 cm. apart in streamwise (x) position



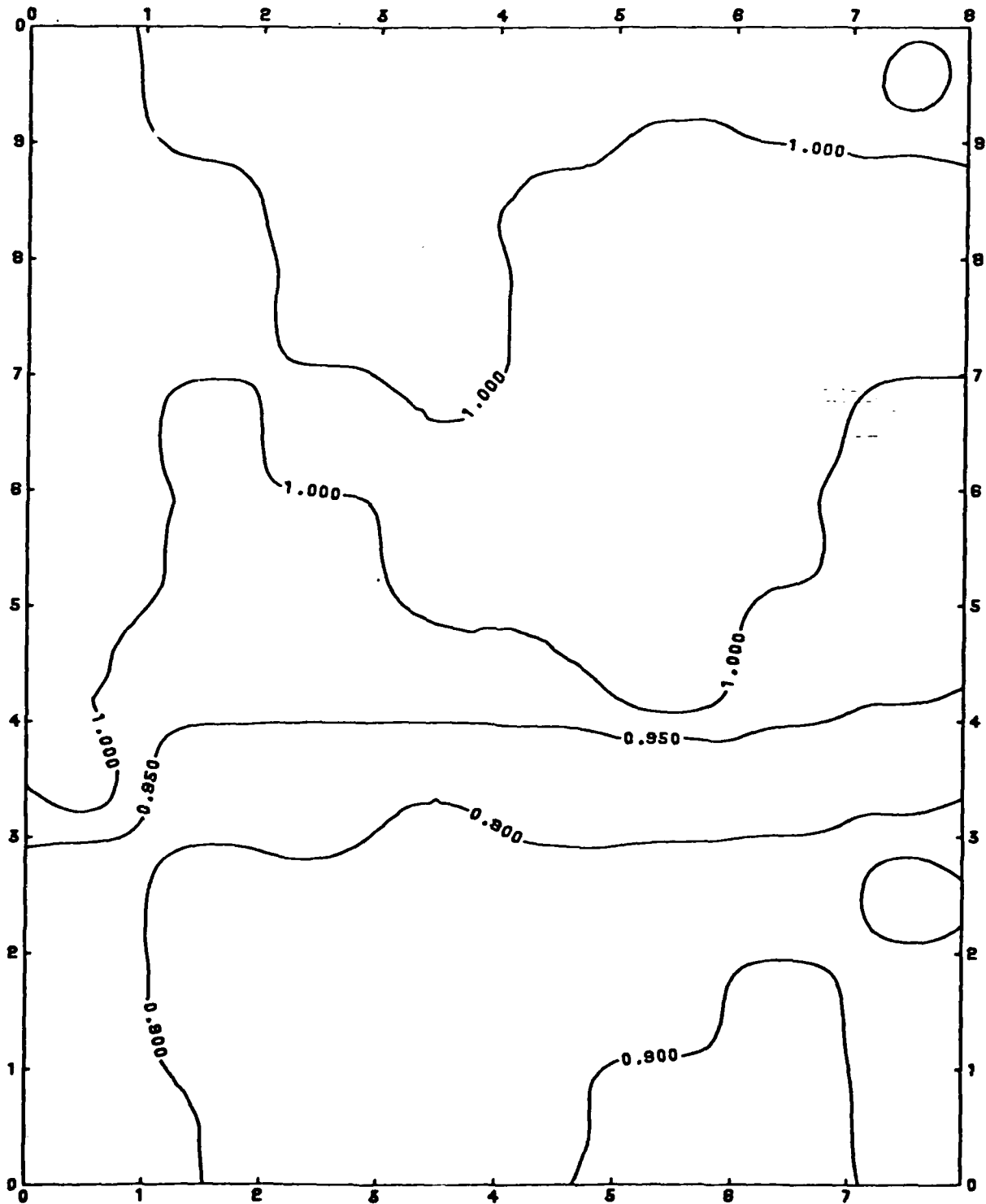
View c Flat wall downstream of curved region from  
 $x = 730$  cm. to  $x = 770$  cm,  $U_e = 15.2$  cm/s



View d Curved wall and inlet wall at low speed,  
 $U_e = 6.1$  cm/s

Figure II-3 Dye injected into wall layers through two spanwise slots  
 30.5 cm. long and 20.3 cm. apart in streamwise (x) position

FIGURE 11-4

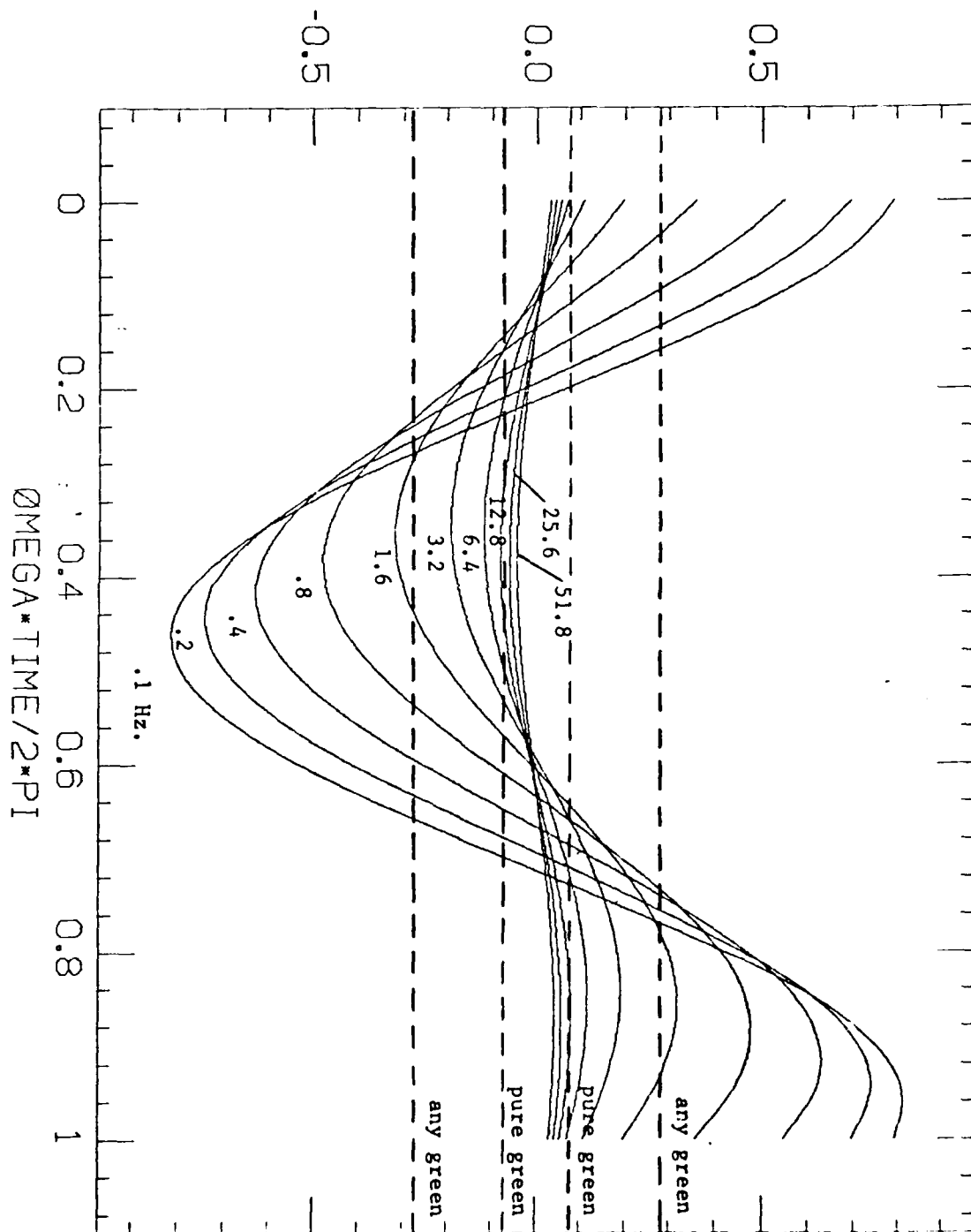


TYPICAL GOLD FILM HEAT FLUX CONTOURS  
(HEAT TRANSFER OUTPUT / AVERAGE POWER DENSITY INPUT)

# SINUSOIDAL HEAT FLUX

FIGURE II-5

$$T(0) - T(0)_{SS}$$



# SINUSOIDAL HEAT TRANSFER COEFFICIENT

FIGURE 11-6

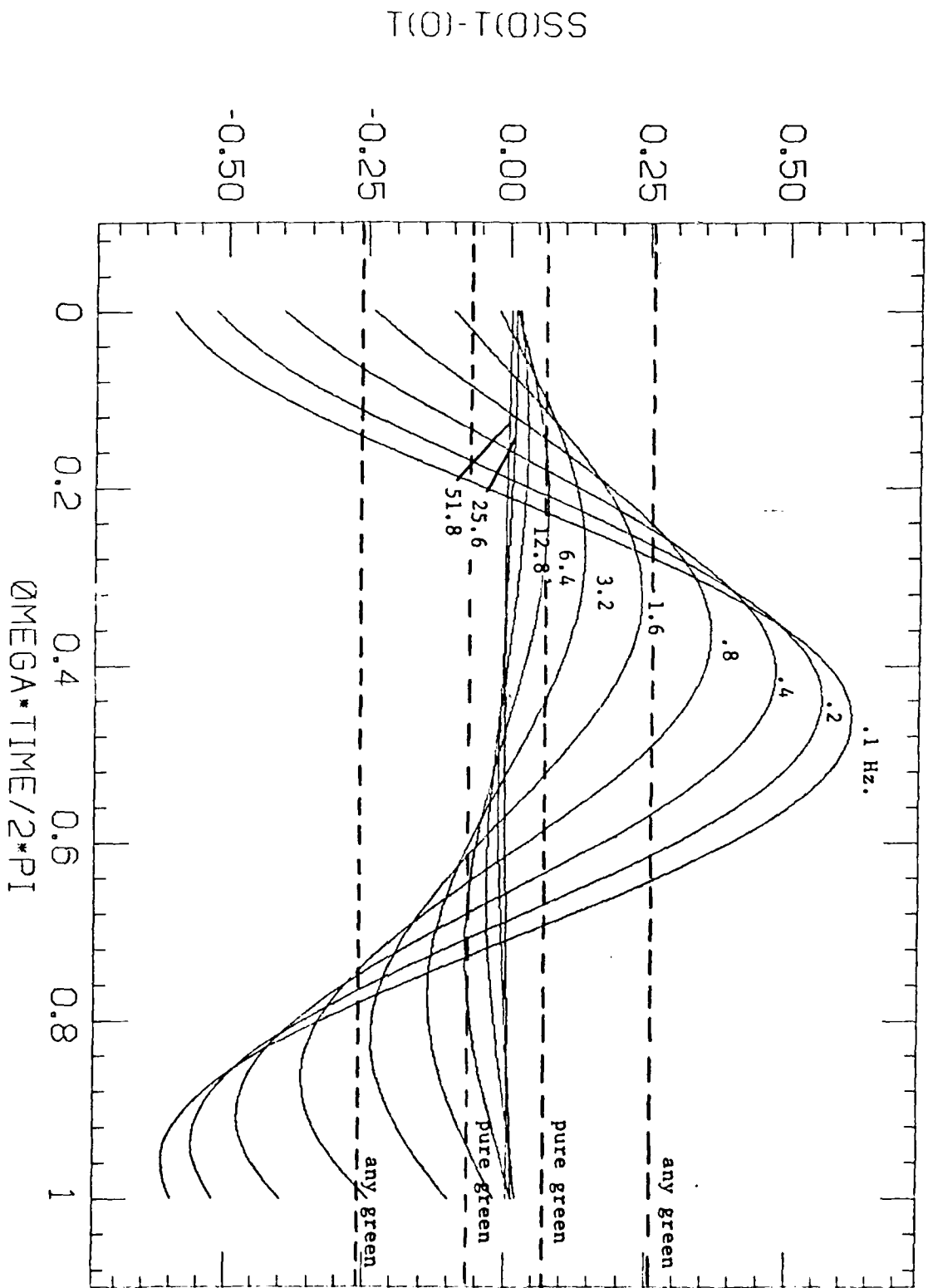
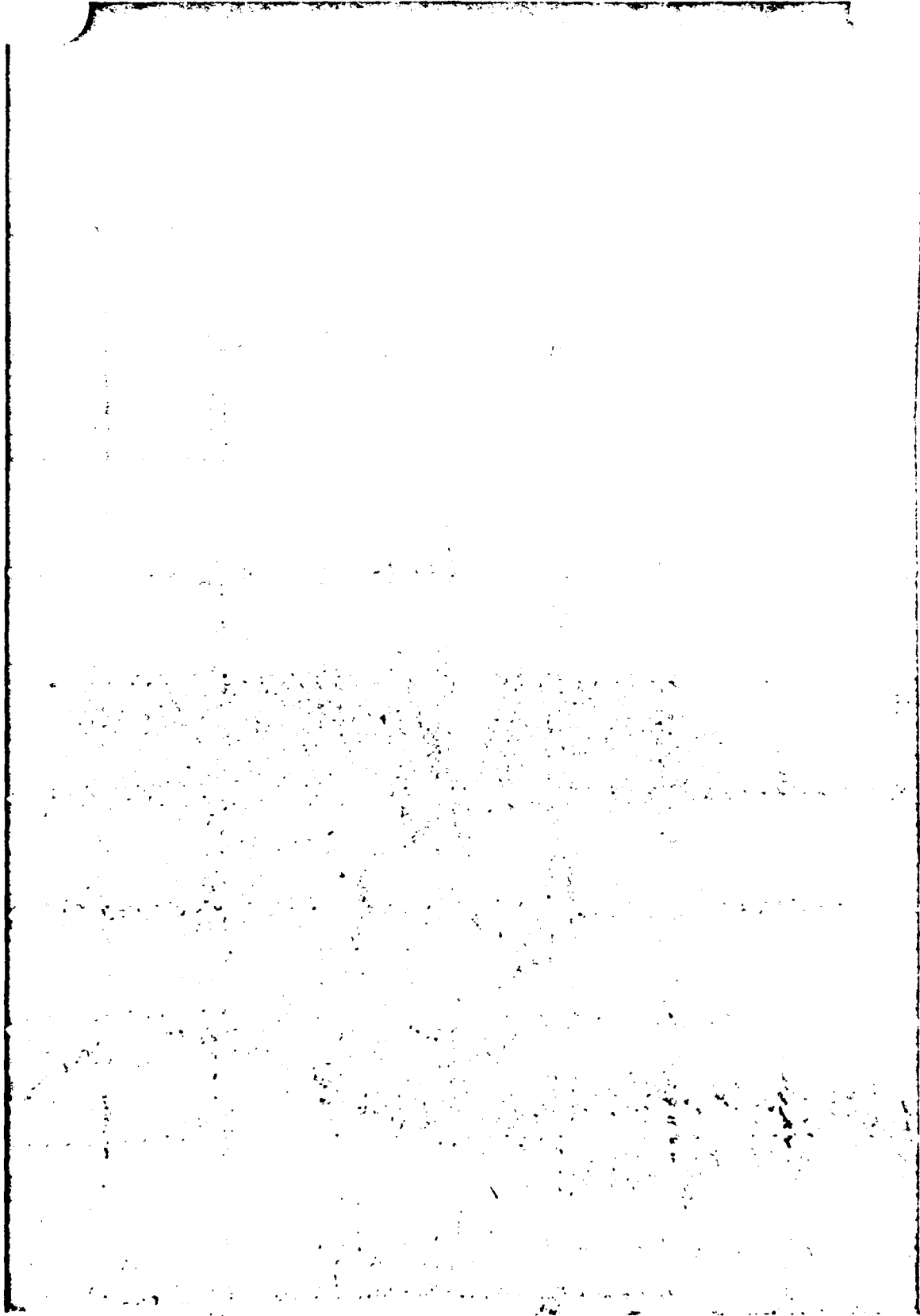


FIGURE II-7



VISUALIZATION OF ISOCHROMES FOR FLOW OVER CIRCULAR CYLINDER STANDING ON PLATE  
FLOW LEFT TO RIGHT